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THE 2MASS WIDE-FIELD T DWARF SEARCH. V. DISCOVERY OF A T DWARF VIA METHANE IMAGING

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ABSTRACT

We present the discovery of a T dwarf, 2MASS 2151−4853, via differential imaging through methane filters. The filters are designed to highlight the strong absorption in the *H* band due to methane found in the atmospheres of T dwarfs and provide a very efficient means of searching for them. Subsequent *J*- and *H*-band spectroscopy confirms 2MASS 2151−4853 as a T dwarf of type T4.5. It has an estimated spectrophotometric distance of 18 ± 3 pc and an estimated tangential velocity of $v_t = 50 \pm 10$ km s^{-1}.

Key words: stars: individual (2MASS J21513839−4853542) — stars: low-mass, brown dwarfs

1. INTRODUCTION

T dwarfs are the coolest ($T \lesssim 1500$ K; Vrba et al. 2004; Golimowski et al. 2004) and least luminous brown dwarfs observed. With atmospheres rich in molecular gases and condensate clouds (e.g., Ackerman & Marley 2001), these sources represent a class of object intermediate between giant planets and low-mass stars.

In the cool atmospheres of T dwarfs, methane and water vapor are formed in abundance. These give rise to broad absorption features in the near-infrared, which distinguish T dwarfs from hotter brown dwarfs in which the production of atmospheric methane is prohibited by collisional dissociation (Noll et al. 2000). These prominent CH_4 and H_2O features have been used to construct schemes of spectral classification for these objects (Burgasser et al. 2002; Geballe et al. 2002). Because of their low photospheric temperatures, an understanding of the atmospheres of T dwarfs is likely to yield important clues about the nature of giant planetary atmospheres.

A statistically complete census of T dwarfs is highly desirable in an effort to extend our understanding of the initial mass function to lower masses, but cataloging T dwarfs can be a time-consuming process. With faint intrinsic magnitudes and near-infrared colors similar to most main-sequence stars, T dwarf candidates can be buried in an overwhelming number of background sources. Traditional spectroscopic follow-up of large samples is extremely time-consuming and has typically had low rates of success. Tinney et al. (2005) describe a new method for simplifying the search process, based on imaging through CH_4 filters. Here we describe a new T dwarf discovered by this method.

Section 2 summarizes the project and the methane imaging process. Section 3 describes the observations and empirical properties of the new T dwarf, 2MASS J21513839−4853542 (hereafter 2M2151−4853). Conclusions are given in § 4.

2. THE 2MASS WIDE-FIELD T DWARF SEARCH AND METHANE IMAGING

The Two Micron All Sky Survey (2MASS) Wide-Field T Dwarf Search is an attempt to conduct a census of the T dwarf population over most of the sky. The selection process is described in detail by Burgasser et al. (2003b) and is summarized here.

The initial sample has been culled from the 2MASS All Sky Working Database (Skrutskie et al. 1997; Cutri et al. 2003) via color and magnitude selection. Areas within a Galactic latitude $|b| < 15°$ have been excluded to avoid regions in which source confusion will be problematic. Likewise, the Magellanic Clouds and other dense source regions have been omitted. To facilitate follow-up observations, regions within 2° of the equatorial poles have also been omitted. In total, the search covers 74% of the sky.

From this sample, objects have been selected with $J - H \leq 0.3$ or $H - K_s \leq 0$, $J \leq 16$ and no counterpart in the USNO-A2.0 catalog (Monet et al. 1998), effectively, $R - J > 4$. This range of color is sufficiently broad to accommodate warmer T dwarfs as early as type T1 (Tinney et al. 2005).

This selection process yields over 250,000 targets. Since it is expected that there will only be 20–30 T dwarfs in this sample (Burgasser et al. 2003b), further discrimination of the targets has been made on the basis of visual classification by A. J. B. and M. W. M., leaving ∼1500 targets. Targets from this list are being observed as part of a methane imaging program.

Our methane imaging program of 2MASS T dwarf candidates is described in full by Tinney et al. (2005). Images were taken

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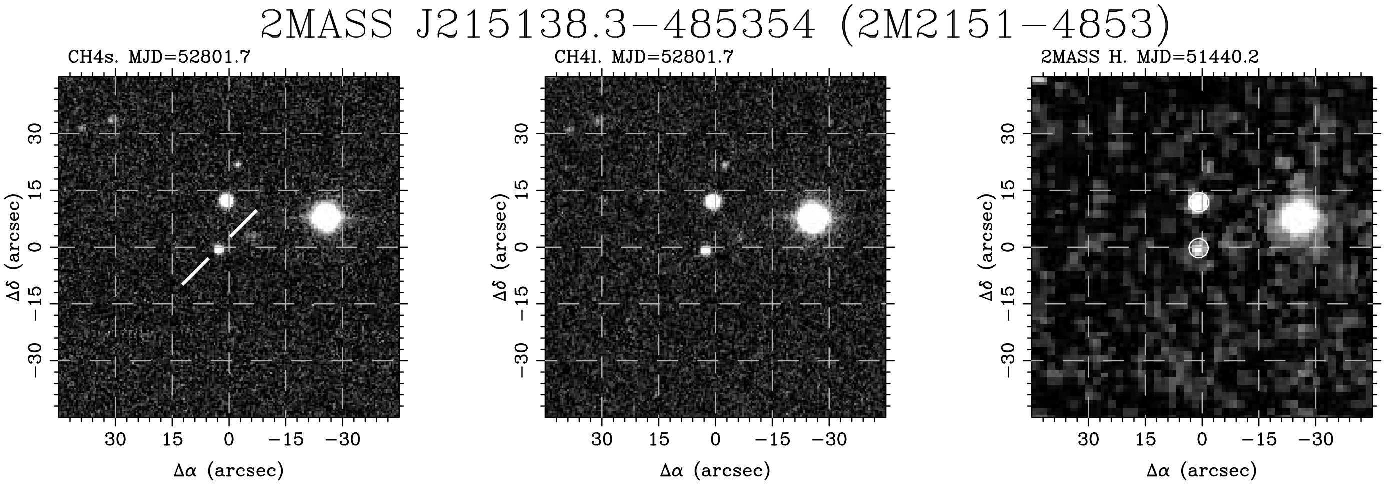

FIG. 1.—Finding chart for 2M2151−4853. The images are 1.′5 on a side, centered on the 2MASS coordinates R.A. = $21^h51^m38^s.39$, $-48°53'54''.2$, and oriented with north up and east to the left. The slight offset from the 2MASS coordinates illustrates the substantial proper motion of 2M2151−4853 of $0''.57 \pm 0''.07$ yr^{-1}; see § 3.4.

through the CH_4s and CH_4l filters with the infrared camera and spectrograph (IRIS2) on the 3.9 m Anglo-Australian Telescope, Siding Spring, Australia.

The CH_4l filter covers the wavelength range of the strong methane absorption features in the infrared *H* band, which define the spectral type T dwarfs (Geballe et al. 2002). Meanwhile, the CH_4s filter samples a wavelength range outside the methane absorption (although within the range of absorption by other molecules, such as H_2O).

The methane observations were calibrated via a series of extensive observations described in Tinney et al. (2005). Stars of known spectral standard were observed and then calibrated according to observations of A, F, and G stars, which show virtually no color variation in $CH_4s - CH_4l$, and K and M stars, for which the methane colors have been empirically calibrated.

3. OBSERVATIONS

3.1. *Methane Imaging*

Methane observations of 2M2151−4853, as described above, were made on 2003 June 11 (UT), in patchy cloud cover (which appears not to have affected our imaging) and 1.″1 seeing. Exposures of 30 s in each of the CH_4s and CH_4l filters were made. Images were dark-subtracted and flat-fielded using standard procedures with the pipeline reduction software ORAC-DR. The flat fields were made by median-combining jittered images of the targets. Finding charts extracted from these images and the 2MASS *H*-band image are shown in Figure 1. SExtractor (Bertin & Arnouts 1996) was used to measure magnitudes in fixed apertures of ≈2.″5 diameter. The differential photometry was calibrated using the procedure described in Tinney et al. (2005) using 2MASS sources in the field to produce Figure 2.

A plot of $CH_4s - CH_4l$ versus CH_4s is shown in Figure 2, with 2M2151−4853 clearly visible above the other objects in the field. A comparison of the methane color of 2M2151−4853 with the calibrated methane colors of A stars through T dwarfs is shown in Figure 3, taken from Tinney et al. (2005). The color of $CH_4s - CH_4l = -0.15 \pm 0.03$ suggests that 2M2151−4853 is of type T2.5 ± 1. Figure 3 highlights the power of the methane imaging methodology. Short images of the target field are made through the CH_4 filters. Any T dwarfs present in the field will be immediately obvious in a plot of $CH_4s - CH_4l$, standing out prominently from the locus of points made up from the hotter stars. Furthermore, a first estimate of spectral type within the T dwarf class can be made from the methane color. Thus, only T dwarf candidates with unusual methane colors need to be followed up with spectroscopic observations.

3.2. *Spectroscopy*

Hs-band (a spectroscopic *H*-band filter covering wavelengths 1443–1824 nm) spectroscopy of 2M2151−4853 was obtained using IRIS2 on 2004 June 23 (UT). The seeing was ∼1.″1, and there was patchy cloud cover. This spectrum was taken with a very low signal-to-noise ratio, sufficient to identify 2M2151−4853 as a T dwarf but not to classify its spectral type. Higher signal-to-noise ratio spectra were then obtained on 2004 August 22 (UT) under good conditions (seeing ∼1.″2 and clear sky) in the Hs and Jl (a spectroscopic *J*-band filter covering wavelengths 1100–1350 nm) bands. The total exposure was 15 minutes in

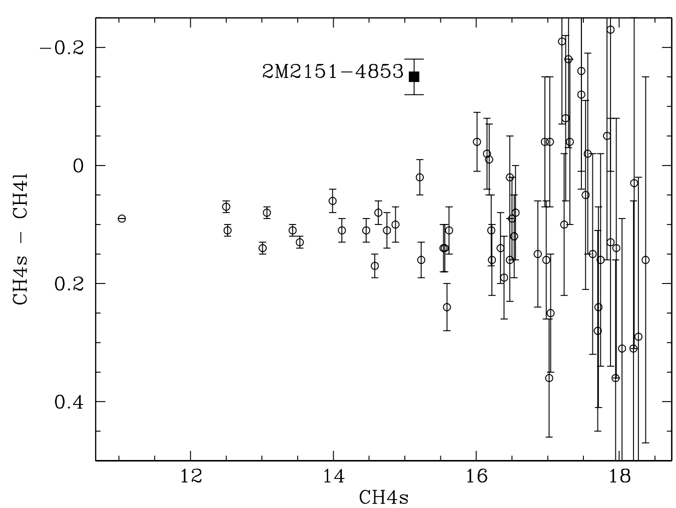

FIG. 2.—$CH_4s - CH_4l$ vs. CH_4s color-magnitude diagram. The source 2M2151−4853 is plotted as a square and is obvious at $CH_4s = 15.13$ by its excess methane color.

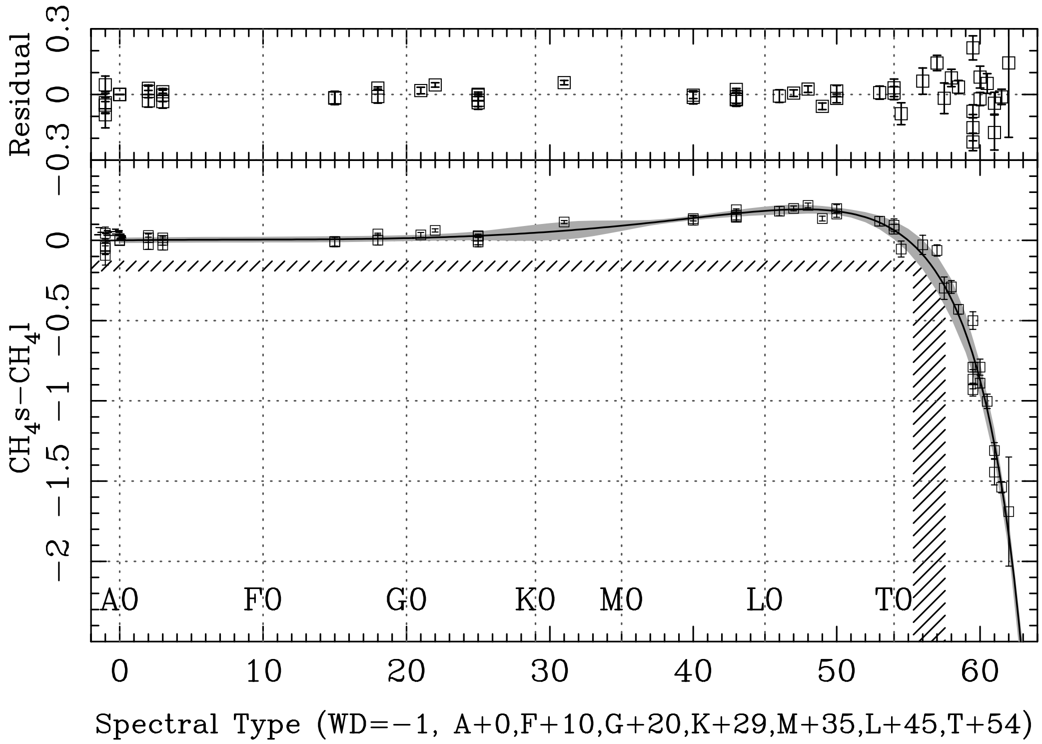

Fig. 3.—Methane color as a function of spectral type. The shaded region around the curve represents the uncertainties derived from photon counting statistics, aperture correction uncertainties, and photometric calibration uncertainties. The horizontal and vertical hatched regions represent the methane color and uncertainty of 2M2151−4853 and the corresponding spectral type. See Tinney et al. (2005) for full details.

each band. The spectra were flat-fielded using dome flats created from a lamp-on-lamp-off sequence. The wavelength calibration was achieved through imaging of a Xe arc lamp. The flattened spectra were divided by a normalized spectrum of a G dwarf telluric standard star to remove the effect of absorption bands.

The final spectra, binned by a factor of 6 to improve the signal-to-noise ratio, are shown in Figure 4, along with the spectra of the T4.5 dwarf, 2MASS J05591914−1404488 (hereafter 2M0559−1404; Burgasser et al. 2000; Tinney et al. 2005). The distinctive absorption features due to H_2O and CH_4 are clearly visible and are identified at the top of each figure, along with the K i absorption lines in the Jl band.

Spectral classification schemes have been devised by Burgasser et al. (2002) and Geballe et al. (2002). We have used the spectral indices of both schemes within the wavelength range of our spectra to check the classification based on the methane colors described above.

Both schemes define spectral indices based on distinctive H_2O and CH_4 features in T dwarf spectra. Burgasser et al. (2002) define the diagnostics given in equation (1), based on the

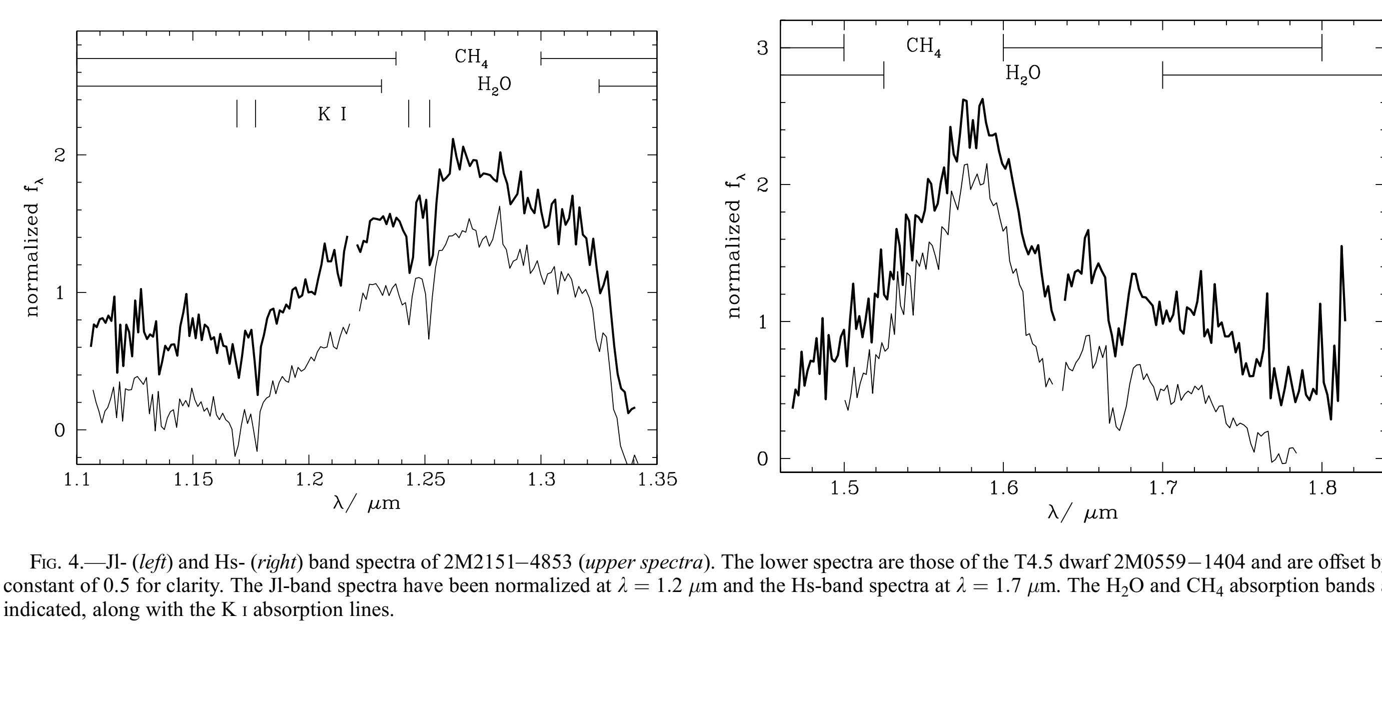

Fig. 4.—Jl- (*left*) and Hs- (*right*) band spectra of 2M2151−4853 (*upper spectra*). The lower spectra are those of the T4.5 dwarf 2M0559−1404 and are offset by a constant of 0.5 for clarity. The Jl-band spectra have been normalized at $\lambda = 1.2$ μm and the Hs-band spectra at $\lambda = 1.7$ μm. The H_2O and CH_4 absorption bands are indicated, along with the K i absorption lines.

TABLE 1
Photometry and Derived Distances

Parameter	J	H	K/K_s
Apparent magnitude 2M2151 (2MASS)	15.73 ± 0.08	15.17 ± 0.10	15.43 ± 0.18
Apparent magnitude 2M2151 (CIT)[a]	15.55 ± 0.08	15.22 ± 0.10	15.57 ± 0.19
Expected absolute magnitude (2MASS; Tinney et al. 2003)	14.0 ± 0.4	. . .	14.0 ± 0.4
Expected absolute magnitude (CIT; Vrba et al. 2004)	14.5	14.3	14.2
Derived distance (pc) (Tinney et al. 2003)	23	. . .	19
Derived distance (pc) (Vrba et al. 2004)	16	15	19

[a] Calculated from the near-infrared color transformations of Stephens & Leggett (2004).

mean flux within the regions of interest and those of a neighboring region of the spectrum outside the absorption feature, and calculate their ratio. For the case of 2M2151−4853 we have

$$\begin{aligned} H_2O - A &= \frac{\langle F_{1.12-1.17}\rangle}{\langle F_{1.25-1.28}\rangle} = 0.37, \\ H_2O - B &= \frac{\langle F_{1.505-1.525}\rangle}{\langle F_{1.575-1.595}\rangle} = 0.46, \\ CH_4 - A &= \frac{\langle F_{1.295-1.325}\rangle}{\langle F_{1.25-1.28}\rangle} = 0.81, \\ CH_4 - B &= \frac{\langle F_{1.640-1.700}\rangle}{\langle F_{1.575-1.595}\rangle} = 0.49, \end{aligned} \quad (1)$$

where the subscripts denote the wave bands of interest in microns. Burgasser et al. (2002) list index values for T dwarf standards in their Table 10. A comparison with that table shows that 2M2151−4853 lies between types T3 and T5 for all the diagnostics (there is no type T4 standard listed).

Geballe et al. (2002) define similar indices based on the integrated flux from diagnostic regions of T dwarf spectra. Computing their indices for 2M2151−4853, we find

$$\begin{aligned} CH_4 \text{ index} &= \frac{\int_{1.56}^{1.60} f_\lambda \, d\lambda}{\int_{1.635}^{1.675} f_\lambda \, d\lambda} = 1.82, \\ H_2O \text{ index} &= \frac{\int_{1.26}^{1.29} f_\lambda \, d\lambda}{\int_{1.13}^{1.16} f_\lambda \, d\lambda} = 2.66, \end{aligned} \quad (2)$$

where the limits of the integrals are given in microns. Geballe et al. (2002) present a look-up table of indices for different spectral types. Comparing to this (Table 5 in their paper), we find that the CH_4 and H_2O indices indicate that 2M2151−4853 is of types T5 and T4, respectively.

A hybrid system uniting the schemes of Burgasser et al. (2002) and Geballe et al. (2002) is in development, using a unified set of fundamental T dwarfs and spectroscopic indices (Burgasser et al. 2005). We compared a subset of the revised spectral indices for this scheme (presented in Burgasser et al. 2003a) with the spectrum of 2M2151−4853 and those of a set of T dwarf comparison sources (Tinney et al. 2005). These indices yield a mean spectral type of T4.5 for 2M2151−4853, consistent with the above indices. This classification is further verified by the similarity of J- and H-band spectra with that of 2M0559−1404 (Fig. 4), itself a T4.5 dwarf (Geballe et al. 2002).

3.3. *Spectrophotometric Distance*

The 2MASS photometry available for 2M2151−4853 has been used to derive an estimate of distance. We have compared the 2MASS magnitudes to the spectral type–absolute magnitude relations given by Tinney et al. (2003) and Vrba et al. (2004). In order to make the comparison with Vrba et al. (2004), the 2MASS magnitudes were first transformed to the California Institute of Technology (CIT) magnitude system using the relations of Stephens & Leggett (2004). The results are given in Table 1.

The distances calculated from the relations of Tinney et al. (2003) and Vrba et al. (2004) are 21 ± 2 and 17 ± 2 pc, respectively. The average distance using all relations is 18 ± 3 pc, assuming it is single.

3.4. *Proper Motion*

2M2151−4853 has an appreciable proper motion measured at $0''.57 \pm 0''.07$ yr^{-1} with a position angle of $113° \pm 3°$, based on the difference in position of the 2MASS images and the methane images. Using the distance estimate derived above, this translates to a tangential velocity of $v_t = 50 \pm 10$ km s^{-1}.

4. CONCLUSIONS

The discovery of 2M2151−4853 further emphasizes the power and efficiency of methane imaging in searching for T dwarfs. This method has been used with great success in the 2MASS Wide-Field T Dwarf Search, as demonstrated in Tinney et al. (2005).

We have used the spectral classification schemes of Burgasser et al. (2002, 2005) and Geballe et al. (2002) to classify 2M2151−4853. All schemes are consistent with 2M2151−4853 being of type T4.5. This is confirmed in a comparison of the spectra of 2M2151−4853 with those of the T4.5 dwarf 2M0559−0414. Spectrophotometric distances indicate it is at a distance of 18 ± 3 pc, and its proper motion implies a tangential velocity of $v_t = 50 \pm 10$ km s^{-1}, consistent with disk population kinematics. The properties of 2M2151−4853 are summarized in Table 2.

TABLE 2
Summary of the Properties of 2M2151−4853

Parameter	Value
R.A. at 2003 June 11 (UT J2000.0)	21 51 38.6
Decl. at 2003 June 11 (UT J2000.0)	−48 53 55
2MASS J (mag)	15.73 ± 0.07
2MASS H (mag)	15.17 ± 0.10
2MASS K_s (mag)	15.43 ± 0.18
CH4s (mag)	15.13 ± 0.02
CH4l (mag)	15.28 ± 0.02
Proper motion (arcsec yr^{-1})	0.57 ± 0.07
Position angle (deg)	113 ± 3
Distance (pc)	18 ± 3
Tangential velocity (km s^{-1})	50 ± 10

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

A total of 11 T dwarfs have now been identified in the 2MASS sample via methane imaging; however, our candidate sample is not yet exhausted. Further discoveries and a final accounting of the search will be provided in a forthcoming paper.

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